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STRESS CORROSION OF HIGH STRENGTH STEELS AND ALLOYS: ARTIFICIAL ENVIRONMENT

Research Project No. 389-1

Sponsored by
U. S. Army Ordnance, Frankford Arsenal
Mr. H. Rosenthal, Contract Monitor

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ABSTRACT

Assigned objectives, test methods, and apparatus for the Project's research program in the field of stress corrosion for high strength steels and alloys are presented.

All data accumulated during the contract year are given. The chemical analyses and physical properties of the assigned steels and alloys, including D6Ac, 300 M, Vascojet 1000, AM355, PH15-7 Mo, and B120VCA, are shown. Other missile materials, including 4137 Co, R270 and Ardeform 301, are also included in the survey.

The heat-treating surveys for all alloys have been completed, and the data are given in both tabular and graphical form.

Cumulative U-bend and bent beam test data on a number of the foregoing materials are presented.

I. INTRODUCTION

Lowering of the so-called "design safety factor" to a near-unity value for rocket motor cases, missile structural components, and airborne vehicles of various types has brought about the present study regarding the contribution of stress corrosion to in-service failure of fabricated components. In addition, while the use of high strength steels is largely confined to the missile field at present, these materials may conceivably become more commonly used in the more conventional construction fields as further fabrication and structural design advances become available.

The project research described herein represents a portion of a grant made available by Army Ordnance for the purpose of promoting a general scientific advancement in the missile materials field. This specific project is concerned with the synthetic environmental stress corrosion testing of high strength steels and alloys. The work will be coordinated with a similar study being performed by Aerojet General Corporation of Azusa, California. Aerojet will utilize natural and production environments for stress corrosion studies on these same materials.

Research Objectives

In conducting a study of stress corrosion cracking of high strength steels and alloys, the Fellowship is committed to the following research objectives:

1. A study of the susceptibility of rocket motor case materials to stress corrosion.
2. A study of the environmental parameters which affect the rate and extent of this corrosion; included in this work will be the atmosphere both on the outside and inside of the rocket case.
3. Determine the effect of material parameters on the stress corrosion process, including composition, strength level, welding, microstructure, surface condition, etc.
4. Devise techniques for preventing stress corrosion in rocket motor cases by methods such as paint systems, shot peening, alloy modification, etc.

In the performance of the foregoing objectives, the following classes of rocket motor case materials will be utilized as sample material for stress corrosion specimens:

1. Low alloy martensitic steel.
2. Silicon-modified 4300 series steel.
3. Hot-worked die steel.

4. Cold-worked PH steel.

5. Heat-treated PH steel.

6. Precipitation hardening stainless steel.

7. High strength titanium alloy.

Stress corrosion specimens of the above materials will be exposed to a variety of synthetic or artificial environments to facilitate the performance of screening tests in attempting to determine preferential susceptibility, if such is the case. While the chemical complexity of a natural environment is extremely difficult if not impossible to duplicate, the use of a simple synthetic environment will allow the determination of stress corrosion susceptibility as a function of a clearly defined reagent. It follows that, by utilizing a number of such synthetic environments, it is probable that the substances or combinations of substances causing stress corrosion of rocket motor cases in natural environments will thereby be determined.

Each of the steels noted previously will be heat treated or otherwise worked to four yield strength (0.2% offset) test levels. It is not expected that these stress levels will be exact in every case but they serve instead as aims. The titanium alloy material stress level aims will be decrease to approximately conform with the 60% strength/weight ratio between titanium and steel. The yield strength test level aims include:

Steel Alloy	Titanium Alloy
200 Ksi	140 Ksi
220	150
240	170
Max.	Max. (about 200 Ksi)

The stress corrosion specimens will be stressed in tension on one side to 75 per cent of the foregoing yield strength test levels during testing by the bent beam test method and to some stress level between the Y.S. and F.S. for the U-bend test method.

A discussion of the test methods is presented in a following section of this report.

Report Scope

This report presents all cumulative information obtained by the Project during the past year of operation. Data on continuing bent beam and U-bend stress corrosion tests, as-received physical test results, and heat treatment surveys for the assigned steels and alloys are given in following sections of this report.

In addition, a number of drawings and schematic diagrams of apparatus and test methods pertinent to the project are also presented.

Steel Alloy	Titanium Alloy
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II. DISCUSSION

Corrosion may be regarded as being subdivided into two broad categories: 1. general corrosion, and 2. localized corrosion. The latter may be further subdivided into pitting and catastrophic types. Stress-corrosion cracking is a localized, catastrophic phenomenon of argumentative origin. This program will be mainly concerned with stress corrosion as it affects high strength steels and alloys in synthetic environments.

Considerable effort has been expended in the past on studies involving stress corrosion of such non-ferrous metals and alloys as aluminum and brass. Austenitic stainless steel has received much attention over the past five to ten years and is still the subject of considerable corrosion research. In spite of this effort, the research area of stress-corrosion cracking of stainless steel is, in the words of Professor H. H. Uhlig[1] of M.I.T., "....one of the major gaps in research development."

High strength steels and alloys have only recently begun to receive attention, due to the fact that this type of ferrous alloy material is now being utilized at or near its maximum strength level. The absence of a general mechanism to explain the phenomenon of stress

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1 Metalworking News, April 17, 1961, p. 18.

corrosion under all circumstances is the driving force behind present research in this area of study.

With regard to information on stress corrosion as provided by the literature, this Project has presented a partial coverage of industrial research references (Report No. 2) and government-sponsored research references (Report No. 3) on the subject. It should also be noted that the Defense Metals Information Center at Battelle[1] is compiling considerable information from a number of sources that is directly related to the work conducted by this Project.

Many excellent papers have been published on stress corrosion research. Some have directly related galvanic or electrolytic attack to stress corrosion cracking and others have attributed the phenomenon to physical causes, such as dislocation density or stacking faults coupled with dislocation generation (associated with a Frank-Bead, Z-mill, etc., sources). The electrochemical mechanism theory is supported by the work of Dix[2], Hoar[3], Evans[4], Logan[5] and Van Rooyen[6], while the

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1 Environmental and Metallurgical Factors of Stress-Corrosion Cracking in High Strength Steels, Defense Metals Information Center, Battelle Memorial Institute, Contract No. AF 33(616)-7747.

2 E. H. Dix, et al, Symposium on Stress-Corrosion Cracking of Metals, ASTM-AIME (1945).

3 T. P. Hoar and J. G. Hines, "Stress-Corrosion Cracking of Austenitic Stainless Steels in Aqueous Chloride Solutions," Stress-Corrosion Cracking and Embrittlement, W.D.Robertson,Wiley and Sons (1956),pp.107-125.

4 U. R. Evans,"On the Mechanism of Chemical Cracking," Stress-Corrosion Cracking and Embrittlement,W.D.Robertson,Wiley and Sons (1956),pp.158-162.

5 H. L. Logan, J.Nat.Bureau of Stds., 48, (1952),p. 99; 61 (1958);p.503.

6 D. Van Rooyen, "Qualitative Mechanism of Stress-Corrosion Cracking of Stainless Steels," Corrosion (1960), 16, p. 421t.

physical mechanism is probably best exemplified by the work of Coleman, et al[1].

Although this Project is not expected to provide a final solution to the high strength steel stress corrosion problem, extensive data will be obtained to show the degree of correlation amoung the variables studied, the relation of same to other work, and to provide at least one probable first-step remedy for the phenomenon. It is also anticipated that the data will more closely define the limitations, if any, beyond which stress corrosion failure may be expected to occur.

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1 E. G. Coleman, D. Weinstein, and W. Rostoker, "On A Surface Energy Mechanism for Stress-Corrosion Cracking," Acta. Met., 9, No. 5, May (1961), p. 491-496.

III. EXPERIMENTAL PROCEDURES

1. Sample Material

The selected high strength steels and alloys representative of the six assigned groups to be stress-corrosion tested include:

1. Low Alloy: Ladish D6Ac
2. Si-Modified 4300 Series: 300M
3. Hot-Worked Die Steel: Vascojet 1000
4. Cold-Worked PH Steel: AM355
5. Heat-Treated PH Steel: PH15-7 Mo
6. Titanium Alloy: B120VCA

The cold-worked austenitic steel group was previously omitted because high strength steels of this type were not being used by the missile industry in any appreciable quantity. However, a sample of a 25% nickel alloy will be included in the program when the material becomes available.

To the foregoing list of assigned steels and alloys were added: 4137 Co, Rocoloy 270 (both modified 4300 Series) and Ardeform 301 (a stretch-formed 17/7 stainless steel).

All sample material was procured in sheet form to be tested as such.

In addition, sheet material from a number of comparative heats of the assigned steels and alloys was obtained for stress corrosion testing. It is possible that the sample material obtained for any one of the assigned alloys (hereafter termed "primary heats") could be an "off-heat," i.e., a heat having acceptable chemistry and physicals but radically different performance characteristics. In order to ascertain whether any of the primary heats is or is not a representative sample, test specimens have been cut from two or three similar heats of each alloy and will be stress corrosion tested for comparison purposes.

Chemical analyses for each of the steels and alloys obtained to date are given in Table I. All presently available as-received physical test data for these materials are presented in Tables II through VI.

2. Sample Preparation

Where tensile specimens have been or are required, i.e., for physicals on as-received material, heat treating surveys, or heat treating of sample material, they have been cut from the sheet sample to the dimensions shown in Figure 1. Tensiles prepared from as-received, annealed steels (300M, D6Ac, and V-1000) were cut from the parent metal with tool steel cutters, carbide cutting tools being required for the higher strength alloys (AM355, PH15-7 Mo, and B120VCA). Final surface preparation before testing was accomplished with 80 and 120-grit emery paper. The higher strength alloys were very carefully handled to minimize induced heat in the sample, added cold work, and fingerprinting (especially the B120VCA).

At least three tensile specimens were taken from both directions of each type of sheet material, the direction showing the lower yield strength being arbitrarily taken as the "primary" direction.

The bent beam and U-bend stress corrosion test specimens were sheared or cut (with a carbide cutter) from the various types of sample material to oversize dimensions of plus 1/16-inches to plus 3/32-inches in width (see following section of this report for sample dimensions). Removal of this excess width shows, metallographically, that the cold worked volume along the sheared edge can be subsequently removed by wet-grinding and polishing.

The AM355 material was cold rolled to the approximate required strength levels by the vendor, Wallingford Steel. Thus wet grinding and polishing with 240-grit emery paper constituted the final mechanical preparation for this specific material. All other alloys are being wet ground to width and thickness prior to heat treating. They will subsequently be polished with 120- and 240-grit emery cloth to remove oxidation surface films, as have the 4137 Co samples.

Thicknesses of the as-received materials are shown in Tables II through VI. The lower alloy, high strength steels have been or are in the process of being wet-ground to a 51^{+1}_{-} mil in thickness. This limitation serves two functions: decarb or other as-received surface irregularities are removed and the violence of specimen failure is minimized (bent beam specimens over 60 to 65 mils in thickness have been known to fly considerable distances upon fracture). In addition, the general specimen thickness limitations of 30 to 50 mils are more representative of actual missile thickness requirements, which fall within this same thickness range.

3. Stress Corrosion Test Types

Laboratory testing of the high-strength steels and alloys utilizes two types of samples or test methods:

a. The U-Bend Test - The U-bend stress corrosion test utilizes a specimen and holder as illustrated in Figure 2. The test specimen is bent into a V-shape in a bending device and is sprung into a U-shape in a holder (of PVC material or the same material as the specimen). The bottom of the U is bent beyond the yield point and the area of greatest applied stress is that outer surface area immediately adjacent (on either side) to this.

This test method, known as the "quick-and-dirty" stress corrosion test, is capable of producing short term results that are not too consistently reproducible. It is not necessarily comparable with the bent beam test. However, the U-bend test will provide a general indication of a trend among steels, all other variables being equal.

b. The Bent Beam Test - The bent beam stress corrosion test utilizes a non-corrodable holder of the type illustrated in Figure 3. The material selected for this holder, polyvinylchloride (PVC), may be immersed in the test solution without introducing such variables as electrolytic or galvanic corrosion between sample and holder or chemical attack upon the holder by the test solution.

The bent beam specimens are precision-cut to length in accordance with the calculated length necessary to place the middle third of the upper sample surface in tension. The required degree of applied stress is 75% of the yield strength.

A bending device of the type illustrated schematically in Figure 4 is used to bend the specimens sufficiently to facilitate their insertion into the sample holder.

4. Heat Treating Surveys

In order to ascertain the method of heat treatment required to attain the various assigned stress levels for each type of steel or alloy, a number of tensile specimens and accompanying metallographic samples from each alloy were heat treated or aged at various temperatures (or for various time intervals). The yield strength curves thus attained are being used in heat treating the bulk of the various types of sample material to strength prior to stress corrosion testing.

The heat treating procedures and survey results for each of the steels and alloys follow. In each case specific information provided by the vendor of the material was utilized.

a. Low Alloy; D6Ac - The heat treating survey of the Primary Heat of this vacuum consumable-arc melted steel had been completed and the data and curves are presented in Table VII and Figure 5. In making this survey, all specimens (tensile and metallographic) were austenitized at 1550°F for 20 minutes and oil quenched. They were then double-tempered (2 + 1 hours) at 100°F increments over a temperature range of 400 to 1100°F. An air quench followed each temper. Three tensile specimens and one metallographic sample were tempered at each tempering temperature. The heat treating medium was a salt bath in both austenitizing and tempering.

b. Si-Modified 4300 Series; 300M - The heat treating survey of the Primary Heat of vacuum consumable-arc melted 300M has been completed, the data being presented in Table VIII and Figure 6. Tensile and metallographic specimens for this survey were austenitized at 1600°F for 20 minutes, followed by an oil quench. The specimens were then double-tempered (2 + 2 hours) at 100°F increments over the temperature range of from 400 to 1000°F. An air quench followed each temper. Three tensiles and one metallographic specimen were utilized for each tempering temperature. Salt baths were used for both austenitizing and tempering.

c. Hot-Worked Die Steel; Vascojet 1000 - The heat treating survey of the Primary Heat of vacuum-melted Vascojet 1000 has been completed. The data obtained are given in Table IX and the resultant curves in Figure 7. In making this survey, all specimens (tensile and metallographic) were preheated to 1450°F, held for 30 minutes at temperature, austenitized (immediately after preheating without quenching) at 1900°F for 40 minutes, and air quenched. The specimens were then given a triple temper (2 + 2 + 2 hrs.) at 50°F increments over the temperature range of from 800 to 1100°F. Three tensile specimens were heat treated at each tempering temperature. Metallographic samples were also periodically removed for future examination at each tempering temperature increment. Salt baths were used for preheating, austenitizing, and tempering.

d. Cold-Worked PH Steel; AM355 - No heat treating survey was necessary for this air-melted material because it was rolled to strength by the vendor, Wallingford Steel. The yield strength aims of 200, 220, and 240 Kpsi in the primary (transverse) direction were not as closely achieved as might be desired. The difficulties inherent in closely achieving physical property aims are only best appreciated by those directly involved. However, the Y.S. values attained (210, 215, and 226 Kpsi) were sufficient for the purpose of the project, especially in view of the fact that this material has radically different physical properties in the two directions (transverse and longitudinal). This incongruity enabled the attainment of six strength levels for the alloy rather than the three original levels. Table IV of this report presents the as-received physical property data for AM355.

e. Heat-Treated PH Steel; PH15-7 Mo - This material was procured as "Condition C" air-melted sheet alloy, having been cold-rolled to a Y.S. of about 200 Kpsi by Wallingford Steel. PH15-7 material in, for example, the mill-annealed "Condition A", would be unacceptable for further processing by this project in that the high Y.S. aims could not be as well achieved.

The heat treating survey for the Primary Heat of this material has been completed, the data being shown in Table X and the curves in Figure 8. Tensile and metallographic specimens were precipitation-hardened by heat treating all samples in a salt bath for one hour at 100°F increments in the temperature range of from 800 to 1100°F, with intermediate hardening temperatures of 950°F and 1050°F being included. Three tensiles and one metallographic specimen were run for each temperature. Air quenching followed.

f. Titanium Alloy; B120VCA - The high strength titanium vacuum-melted alloy sheet material was received in the solution-treated condition ready for aging. Heat treatment of this alloy required total absence of fingerprints on the sheet surface and an inert atmosphere for aging. The tensiles were cut from the B120VCA sheet, placed in a pyrex glass sample flask (as illustrated schematically in Figure 9) and dry, oxygen-free argon was passed through the system to purge it of air. The sample bottle was then sealed off at both ends and placed in a hearth-type oven for aging at 900°F.

The heat treatment survey for this alloy has been completed. The data obtained are shown in Table XI and the physical property curves in Figure 10. The data indicate that aging times exceeding 120 hours (the longest used) should have been utilized to determine the maximum aging curve peak. However, a reasonable estimate of 200 to 240 hours would very probably produce the maximum yield strength attainable for this alloy.

g. 4137 Co Alloy - Data on the heat treating survey for this vacuum-melted alloy are illustrated in Table XII and the resulting curves in Figure 11. Austenitizing was performed at 1700°F for 30 minutes, followed by an air quench. Double-tempering (2 + 1 hours) was accomplished at varying temperature intervals between 400 and 1000°F, each temper being followed by an air quench. Both processes were carried out in salt baths.

The data presented for this alloy are on the low side, the maximum yield strength attainable being in the 250 Kpsi range and varying mainly with carbon content.

h. Rocoloy 270 Alloy - Data on the heat treatment survey for air-melted (vacuum-melted not shown) R270 are presented in Table XIII and the curves in Figure 12. Austenitizing was performed at 1700°F and double-tempered (2 + 1 hours) at temperatures varying from 400 to 850°F. Both steps were carried out in a salt bath.

i. Ardeform 301 - This material was received in the fully heat-treated and cold-worked condition. The pertinent data are presented in Table VI of this report.

5. Stress Corrosion Testing

The authors are indebted to Dr. E. H. Phelps and Mr. A. W. Loginow of the U. S. Steel Applied Research Laboratory, Monroeville, Pa., for their invaluable aid in providing information pertinent to stress corrosion testing and in supplying tables on tensile stresses in bent beams. The test methods described in their recent publication[1] will be utilized by this Project.

The six assigned groups of steels and alloys for stress corrosion testing by this Project together with the stress level aims for same are given in the Introduction section of this report. The specific materials to be tested are listed under Sample Material, a prior subdivision of this section of the report.

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[1] E. H. Phelps and A. W. Loginow, Stress Corrosion of Steels for Aircraft and Missiles, Corrosion, July (1960), 97-107.

Five test solutions were arbitrarily chosen for stress corrosion testing of the sample material. Each solution has been affiliated with stress corrosion failure of one or more types of steel or alloys, as indicated by the literature. Obviously, the number of test solutions must be restricted to keep the amount of sample preparation within reasonable bounds. The test solutions utilized include:

1. Sodium Chloride ($NaCl$), 1 M
2. Sodium Nitrate ($NaNO_3$), 1 M
3. Sodium Sulfate (Na_2SO_4), 1 M
4. Sodium Phosphate ($NaPO_3$), 1 M
5. Sodium Sulfide (Na_2S), 1 M

All are sodium salts, thereby minimizing hydrogen ion concentration, and all are one molar solutions.

During testing, the solutions will be aerated regularly to obviate possible hydrogen embrittlement interaction and the test samples will be totally immersed in the respective synthetic environments. Testing will be extended as long as possible or until all samples have failed.

6. Miscellaneous Apparatus

As previously stated in this report, the maximum thickness of the stress corrosion sample material under test was limited to 50 mils for both practical and safety pruposes. However, even at this thickness the violent fracture of U-bend specimens was found to be sufficient to cause breakage of laboratory glassware.

Test tanks of the type illustrated in Report No. 3 (page 4) constructed in the laboratory, heavy glass containers, and polyethylene containers are therefore being used for testing in the various synthetic aqueous environments.

An aeration system for the test tanks was designed and constructed by Project personnel to allow daily aeration of test solutions and thereby minimize possible hydrogen embrittlement interactions.

The completed facility is illustrated in Report No. 7, page 4.

IV. EXPERIMENTAL

Sample preparation and heat treatment are discussed in the previous section of this report (Experimental Procedures).

U-bend and bent beam stress corrosion testing of AM355, PH15-7 Mo, 4137 Co, B120VCA and Ardeform 301 in synthetic environments are continuing. Bent beam samples of 4137 Co have also been mounted on an outdoor test rack for heavy industrial environment exposure. Comparative samples of identical 4137 Co material are being stress corrosion tested in semi-industrial and marine atmospheres on a cooperative program with the U. S. Steel Applied Research Laboratory.

In addition to the foregoing, U-bend samples of AM355 and PH15-7 Mo have been subjected to testing in three additional test solutions, other than the five listed in Experimental Procedures. These three include: 1. a chlorinated non-hydrocarbon (CCl_4); 2. a non-chlorinated hydrocarbon (C_5H_{12}); and 3. a chlorinated hydrocarbon ($C_2H_2Cl_4$). It is anticipated that Vascojet-1000 samples will be added to this test group upon completion of the batch heat-treating of this material. The above alloys are used in the fabrication of the B-70 and other airborne vehicles and could conceivably be subjected to environments of the foregoing types or derivatives thereof.

A more comprehensive description of the various tests and the cumulative results to date includes:

1. U-Bend Test Results

A number of U-bend specimens of AM355 (Primary Direction; 226 Kpsi Y.S.) are undergoing testing, the cumulative test results being shown in Table XIV. The data indicate a susceptibility to stress corrosion in the one molar NaCl solution.

U-bend specimens of PH15-7 Mo alloy (as-received material; Primary Direction; 196 Kpsi Y.S.) have been immersed in all five test solutions. As the cumulative data in Table XV show, there have been no failures to date for any of these samples.

Of the AM355 and PH15-7 Mo U-bend samples exposed to the chlorinated-hydrocarbon series of test environments, only one sample failure (in CCl_4) has been recorded to date, as shown in Table XVI. However, the short exposure time for this batch of samples is far too short to anticipate conclusive results.

As Table XVII shows, the B120VCA U-bend specimens (as-received material; Secondary Direction; 135 Kpsi Y.S.) have shown no failures to date in any of three test solutions. More comparable results will probably be forthcoming when the aged or higher-strength specimens similarly exposed.

The cumulative U-bend stress corrosion test results for the 4137 Co samples are presented in Table XVIII. This alloy has been more extensively investigated because it was more easily available and, therefore, provides more conclusive information. Samples of the highest strength level (550°F temper or a Y.S. of 250-260 Kpsi) are shown to be susceptible to all synthetic environments. In addition, the possible existence of a Y.S. stress threshold level in the vicinity of 210-235 Kpsi (a 750°F temper), beyond which stress corrosion is not likely to occur, is indicated.

The 4137 Co material also seems highly sensitive to a phosphate environment. It is probable that the test solution was of the phosphoric acid type and the resulting attack was of such a nature that hydrogen embrittlement may have been the main cause of failure rather than stress corrosion. This probability is supported by the fact that gas evolution accompanied the exposure of the samples and failure, while violent and of short duration, was not necessarily transverse to the specimen length and did not always result from the formation of a single crack.

However, one may postulate that the phosphate test results indicate, for example, that the use of a phosphate-base coating prior to painting on a high strength 4100-series steel, followed by the application of a moderate to high stress, could cause early catastrophic failure of the material.

The effect of water vapor exposure on identical samples of 4137 Co material are shown in Table XIX. Of the three test environments (dry air; variable water vapor content; humid or saturated water vapor environments) only the saturated water vapor environment had an effect on the specimens.

Sample preparation of a stretch-formed stainless steel, Ardeform 301, was presented in Report No. 10. The specimens from Sample Nos. 1 and 2 show some sensitivity to the NaCl environment, as indicated in Tables XX and XXI.

2. Bent Beam Test Results

Stress corrosion testing of the AM355 bent beam specimens is continuing. As Table XXII indicates, there have been no failures to date for any of the samples under test in the five synthetic environments. Comparison of the bent beam results with the U-bend tests is not feasible at present, because all strength levels are not represented.

Cooperative bent beam stress corrosion tests are being conducted with 4137 Co samples by the U. S. Steel Applied Research Laboratory. Specimens of three strength levels are being exposed to a marine environment (Kure Beach, N. C.) and a semi-industrial environment (Monroeville, Pa.). The cumulative test results to date are given in Table XXIII. No change has been noted in the status of these samples over the past month.

Bent beam specimens from the same heat of 4137 Co steel have also been prepared by Project personnel and mounted on the Institute roof for heavy industrial environment exposure. The cumulative results to date are shown in Table XXIV.

A comparison among samples in Tables XXIII and XXIV at the 75% of Y.S. strength level shows that the heavy industrial environment samples have outlasted the samples exposed to the semi-industrial and marine environments. Other than the possibility of sample preparation differences, there is no immediate, obvious answer to this discrepancy.

A threshold strength level, beyond which stress corrosion becomes negligible, is also indicated by the bent beam samples, as well as for the U-bend data. However, the stress level is lower (130 Kpsi Y.S.) in Table XXIII than in Table XXIV (175 Kpsi Y.S.) and both are lower than that indicated by the U-bend samples (210-235 Kpsi Y.S.).

V. CONCLUSIONS

In addition to the probable existence of a threshold strength value, below which catastrophic stress corrosion failure may be non-existent (as discussed in the previous section of this report), observation of the U-bend specimens, in general, has shown that there is a definite incubation and a crack propagation time interval associated with failure of the samples. These effects were noted specifically for both the AM355 and the 4137 Co U-bend samples.

Immersion of the test samples for a period varying from a few hours to a number of days was followed by an audible "click" or "snap", which was, in turn, followed by audible failure of the specimen after a period of seconds to hours.

Obviously, a mechanism of this type is kinetic rather than thermodynamic and may be evaluated eventually on an energy basis. The total energy to failure may be theorized as being a function of the summation of: the applied stress plus the energy due to dislocations, etc., already in the specimen, plus the energy supplied by dislocations being generated at the applied stress level, plus an energy value to account for electrochemical action (with its accompanying weakening of the specimen cross-section by selective attack). The inclusion of an energy function to allow for the electrochemical effect is indicated by the Phelps and Loginow publication, in which cathodic protection was shown to alleviate stress corrosion failure. When the summation of these energies exceeds the total energy required for fracture, the specimen will break. Separating and pinning down these constituent energies will be difficult at best.

Typical fracture types for the U-bent specimens are illustrated in Figure 13. Types A and B have fractured in the area where plastic deformation or yielding has taken place with added applied surface tensile stress. This region would be beyond the Y.S. to an unknown degree. Types C and D have fractured in the area where the surface tensile stress is close to the Y.S. and where the highest applied surface tensile stress

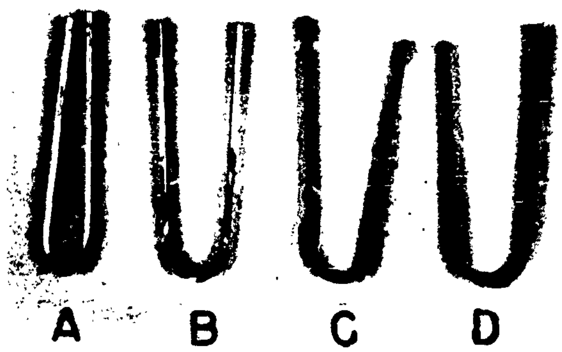

FIG. 13 U-BEND FRACTURE

Types:
A. 4137 Co; Tempered at 750°F
B. 4137 Co; Tempered at 550°F
C. 4137 Co; Tempered at 1100°F
D. 4137 Co; Tempered at 550°F

is located. Type C represents the more common type of break obtained during the testing to date.

A typical bent beam fracture is illustrated in Figure 14. The crack origin was the specimen edge, the most common type of fracture for this type sample.

Although all samples have not been examined, most fractured specimens were of the transcrystalline fracture type, with a single transverse (to specimen length) crack causing failure. Considerable additional work will be necessary before this statement may be considered a generality, however.

FIG. 14 TYPICAL BENT BEAM FRACTURE; OUTDOOR EXPOSURE; 4137 Co STEEL

VI. FUTURE WORK

The immediate objectives over the next month or two include: heat treatment and final sample preparation of PH15-7 Mo, Vascojet 1000, D6Ac, B120VCA, and 300M; metallographic examination and grain size determination of the heat treated cross-sectional samples; continued stress corrosion testing by the bent beam and u-bend test methods of the samples as they become available; and presentation of the cumulative stress corrosion test results.

The long range objectives over the second year of the contract period will include: the effect of various types of coatings on stress-corrosion-prone steels and alloys, based on the test results obtained by the project and indications presented in the literature; stress corrosion testing of new steels and alloys, other than those assigned; and a critical review of the cumulative data obtained. The effect of various interactions of other variables, such as surface carburization or decarburization, with stress corrosion will also receive attention if time is available.

C. J. Owen:grr

Charles J. Owen
FELLOW

W. D. Ruble

William D. Ruble
RESEARCH ASSISTANT

R: 7-6-61
T: 7-17-61

TABLE I

CHEMICAL ANALYSES OF STEELS AND ALLOYS

Steel or Alloy	Sample Designation	Chemical Composition, % by wt.														
		C	Mn	P	S	Si	Cr	Ni	Mo	Al	V	Co	H	N	Ti	Fe
D6Ac	Primary Heat	0.48	0.68	0.007	0.008	0.22	1.23	0.55	1.01		0.06					bal.
D6Ac	Comp. Ht #2	0.48	0.70	0.010	0.002	0.19	1.19	0.62	1.08		0.10					bal.
300M	Primary Heat	0.43	0.66	0.006	0.005	1.80	0.84	1.83	0.35	0.065	0.06					bal.
300M	Comp. Ht #1	0.41	0.70	0.007	0.004	1.50	0.77	1.71	0.37	0.11	0.09					bal.
V-1000	Primary Heat	0.38	0.28	0.010	0.008	0.80	5.10		1.35		0.48					bal.
V-1000	Comp. Ht #1	0.38	0.22	0.009	0.007	0.90	5.19		1.20		0.50					bal.
V-1000	Comp. Ht #2	0.39	0.27	0.009	0.008	0.98	5.12		1.29		0.51					bal.
V-1000	Comp. Ht #3	0.42	0.36	0.011	0.006	0.90	4.90		1.28		0.50					bal.
AM355	Primary Heat	0.14	0.72	0.018	0.018	0.29	15.60	4.38	2.71					0.11		bal.
PH15-7Mo	Primary Heat	0.08	0.54	0.014	0.008	0.26	15.05	7.12	2.16	1.16						bal.
B120VCA	Primary Heat	0.02					11.2	0.02		3.0	13.7		0.018		bal.	0.23
B120VCA	Comp. Ht #1	Not Available														
4137Co	Vac. Melt	Not Available														
R270	Air Melt	0.48	1.01	0.008	0.007	1.38	0.95	1.18	0.45	0.12	0.26	0.96				bal.
R270	Vac. Melt	Not Available														
Arde. 301	Cold Wkd S.S.	0.06	1.52	0.030	0.016	0.49	17.02	7.50								bal.

TABLE II

PHYSICAL PROPERTIES OF D6Ac AND 300M

As-Received Material

Alloy Type	Yield Strength (.2% Offset) Kpsi	Tensile Strength Kpsi	Fracture Strength Kpsi	Reduction in Area %	Elongation 1"	Elongation 2"	Sample Direction*
D6Ac	75	97	162	48.7	27.9	20.1	Primary
Primary Heat	80	96	161	49.3	26.3	18.4	Secondary
D6Ac	57	90	158	59.5	30.8	21.8	Primary
Comp. Ht. No. 1	74	92	160	50.1	28.4	20.7	Secondary
300M	76	102	147	45.2	25.0	19.0	Primary
Primary Heat	83	109	160	43.0	22.0	16.2	Secondary
300M	88	107	168	47.5	30.0	22.0	Primary
Comp. Ht. No. 1	93	108	163	45.7	30.0	20.7	Secondary

Note: Above results are an average of 3 specimens per direction per value indicated.
Nominal specimen thickness: .065" for D6 Prim. Ht.; .060" for D6 Ht. No. 1; .073" for 300M Prim. Ht.; and .078" for 300M Ht. No. 1.
All specimens taken from as-received sheet material.
* The Primary Direction is taken as the direction of lowest Y.S.

TABLE III

PHYSICAL PROPERTIES OF VASCOJET 1000

As-Received Material

Heat Designation	Yield Strength (2% Offset) Kpsi	Tensile Strength Kpsi	Fracture Strength Kpsi	Reduction in Area %	Per Cent Elongation 1"	Per Cent Elongation 2"	Sample Direction*
Primary Heat	75	103	174	51.1	26.7	19.0	Primary
	91	114	187	49.4	27.3	18.8	Secondary
Comparative Heat No. 1	73	103	172	44.4	25.2	17.7	Primary
	89	109	171	46.7	26.4	18.3	Secondary
Comparative Heat No. 2	71	99	101	26.1	29.0	20.5	Primary
	84	106	127	33.9	30.7	20.7	Secondary
Comparative Heat No. 3	74	101	166	32.9	28.4	19.0	Primary
	82	107	182	34.6	26.6	17.2	Secondary

Note: Above results are an average of 3 specimens per direction per value indicated.
The nominal specimen thickness of the Primary Heat was .070" and of the Comparative Heats Nos. 1, 2, and 3: .060", .085", and .100", respectively.
All specimens taken from as-received sheet material.
* The primary rolling direction was arbitrarily chosen as the direction with the lower Y.S.

TABLE IV

PHYSICAL PROPERTIES OF AM355

As-Received Material

Material Strength Level	Per Cent Cold Reduction	Yield Strength (.2% Offset) Kpsi		Tensile Strength Kpsi		Fracture Strength Kpsi	Reduction in Area %	Elongation in 2" %	Final Thickness*, inches
		Mellon	Wallingford	Mellon	Wall.				
Low	36.5	250	251**	261	259**	368	30.4	16	.038
Medium	39	261	259**	271	264**	358	25.3	15	.0365
High	45	302	298**	311	303**	403	22.7	3.8	.033
Primary Heat; Transverse (Lower Y.S.) or Primary Direction									
Low			210		275.5			11	
Medium			215.5		296			7.5	
High			226.5		275.5			11	

Note: Above results are an average of 3 specimens per direction per value indicated. All specimens taken from as-received material.

* Original thickness before cold rolling was 0.060 inches.

** Values obtained by special request from vendor.

TABLE V

PHYSICAL PROPERTIES OF PH15-7Mo, B120VCA, AND ROCOLOY 270

As-Received Material

Alloy Type	Yield Strength (.2% Offset) Kpsi	Tensile Strength Kpsi	Fracture Strength Kpsi	Reduction in Area %	Elongation 1"	Elongation 2"	Sample Direction*
PH15-7Mo Primary Heat	201	238	275	17.9	--	3.5	Primary
	218	221	259	21.2	--	2.5	Secondary
B120VCA Primary Heat	139	140	195	36.4	28.5	19.5	Primary
	143	145	192	35.9	29.0	19.5	Secondary
Rocoloy 270 Vac. Melt Heat	72	112	162	41.7	27.0	18.5	Primary
	77	115	166	40.5	27.5	18.7	Secondary
Rocoloy 270 Air Melt Heat	74	106	151	38.7	23.0	13.3	Primary
	83	109	154	38.9	26.7	14.7	Secondary

Note: Above results are an average of 3 specimens per direction per value indicated.
Nominal specimen thicknesses: .030" for PH15-7; .035" for B120VCA; and .100" for both Rocoloy samples.
All specimens taken from as-received sheet material.

* The Primary Direction is taken as the direction of lowest Y.S.

TABLE VI

PHYSICAL PROPERTIES OF 4137 Co AND ARDEFORM 301

As-Received Material

Alloy Type	Yield Strength (.2% Offset) Kpsi	Tensile Strength Kpsi	Fracture Strength Kpsi	Reduction in Area %	Elongation 1"	Elongation 2"	Sample Direction*
4137 Co Air Melt Heat	101	124	177	37.3	15.5	95.	Primary
Arde 301 Sample No. 1	183	229	293	29.0	10.5	7.7	Longitudinal
Arde 301 Sample No. 2	209	235	295	29.2	9.0	6.0	Longitudinal

Note: Above results are an average of 3 specimens per direction per value.
Nominal specimen thicknesses: .065" for 4137 Co and .055" for both Ardeform samples.
All specimens taken from as-received material.
* The Primary Direction is taken as the direction of lowest Y.S.; refer to following section on sample preparation for Ardeform.

TABLE VII

PHYSICAL PROPERTIES OF D6Ac (PRIMARY HEAT)

HEAT TREATMENT SURVEY

PRIMARY DIRECTION

Tempering Temperature °F	Yield Strength (.2% Offset) Kpsi	Tensile Strength Kspi	Fracture Strength Kpsi	Hardness R_c	Elongation 1"	Elongation 2"	Y.S./T.S.	Reduction in Area %
400	252	299	307	53.8	9.5	6.0	.843	12.4
500	255	280	296	52.3		4.5	.911	14.0
550	254	278	291	51.5	8.0	4.8	.914	16.0
600	244	265	271	51.0	9.0	5.0	.921	15.6
700	238	252	264	49.7	9.0	4.8	.944	17.0
800	227	238	255	47.2	9.0	5.0	.954	16.5
900	215	223	264	45.8		5.8	.964	29.9
1000	205	214	257	44.0	10.0	6.7	.958	25.8

Note: All results are the average of 3 specimens.
Nominal specimen thickness: .066".
Specimens were austenitized at 1550°F for 20 min. and double tempered at the above indicated temperatures for 2 + 1 hrs.

TABLE VIII

PHYSICAL PROPERTIES OF 300M (PRIMARY HEAT)

HEAT TREATMENT SURVEY

PRIMARY DIRECTION

Tempering Temperature °F	Yield Strength (.2% Offset) Kpsi	Tensile Strength Kpsi	Fracture Strength Kpsi	Hardness R_c	Elongation 1"	Elongation 2"	Y.S./T.S.	Reduction in Area %
400	245	304	345	54.5	8.0	5.7	.806	17.8
500	246	294	373	53.8	10.0	5.7	.837	32.3
550	250	295	331	53.0	9.5	5.3	.847	22.2
600	249	296	335	54.0	9.5	5.3	.841	25.0
700	240	277	294	52.5	8.5	5.5	.866	18.9
800	213	250	275	50.0	10.0	6.5	.852	19.3
900	209	237	253	47.0	11.0	6.8	.882	14.8
1000	204	225	267	44.5	12.3	8.0	.907	21.4

Note: All results are the average of 3 specimens.
Nominal specimen thickness: .073".
Specimens were austenitized at 1600°F for 20 min. and double tempered at the above indicated temperatures for 2 + 2 hrs.

TABLE IX

PHYSICAL PROPERTIES OF VASCOJET 1000 (PRIMARY HEAT)

Tempering Temperature °F	Yield Strength (.2% Offset) Kpsi	Tensile Strength Kpsi	Fracture Strength Kpsi	Hardness R_c	Elongation 1"	Elongation 2"	Y.S./T.S.	Reduction in Area %
800	213	309	338	55.3	12.0	9.0	.689	14.4
850	220	318	338	56.0	--	--	.692	--
900	217	314	343	55.8	6.0	3.5	.691	14.0
950	228	320	348	56.0	7.0	4.0	.712	10.4
975	243	313	336	55.2	11.0	7.5	.776	13.0
1000	236	304	328	54.6	11.0	7.2	.776	18.3
1050	232	279	296	51.6	10.0	6.2	.831	18.3
1100	200	240	282	47.3	12.3	7.7	.833	26.2

Note: All results are the average of 3 specimens.
Nominal specimen thickness: .070".
Specimens taken in the secondary (highest Y.S.) direction.

TABLE X

PHYSICAL PROPERTIES OF PH15-7 Mo (PRIMARY HEAT)

HEAT TREATMENT SURVEY

Tempering Temperature °F	Yield Strength (.2% Offset) Kpsi	Tensile Strength Kpsi	Fracture Strength Kpsi	Hardness R_C	Elongation in 2"	Y.S./T.S.	Reduction in Area %
			PRIMARY DIRECTION (lowest Y.S.; transverse to rolling direction)				
800	261	275	312	49.0	1.2	.949	11.8
900	282	293	312	51.0	1.5	.962	8.2
950	277	292	314	51.3	1.7	.949	9.4
1000	278	285	314	51.0	1.5	.975	13.1
1050	255	262	286	48.5	3.0	.973	13.8
1100	224	234	268	44.7	5.7	.975	16.3
			SECONDARY DIRECTION				
800	266	267	302	59.0	1.5	.996	14.3
900	283	283	319	51.0	1.0	1.000	12.3
950	281	282	333	50.8		.996	15.4
1000	283	283	298	50.5	2.0	1.000	14.4
1050	252	258	299	48.2	2.5	.977	17.7
1100	217	227	293	45.0	6.8	.956	29.6

Note: All results are the average of 3 specimens.
Nominal specimen thickness: .030"

TABLE XI

PHYSICAL PROPERTIES OF B120VCA (PRIMARY HEAT)

HEAT TREATMENT SURVEY

PRIMARY DIRECTION

Aging Time Hrs.	Yield Strength (.2% Offset) Kpsi	Tensile Strength Kpsi	Fracture Strength Kpsi	Hardness R_c	Elongation in 2"	$\frac{Y.S.}{T.S.}$	Reduction in Area %
6	140	140	169	27.0	14.0	1.000	19.9
12	141	142	170	28.5	12.0	.993	16.9
24	147	154	169	31.5	5.0	.954	15.4
48	154	165	174	33.0	3.0	.933	5.3
72	164	175	185	36.5	2.5	.937	4.8
120	181	194	215	40.5	2.0	.933	6.8

Note: All results are the average of 3 specimens.
Nominal specimen thickness: .035".
Aging temperature: 900°F.

TABLE XII

PHYSICAL PROPERTIES OF 4137 Co

HEAT TREATMENT SURVEY

PRIMARY DIRECTION

Tempering Temperature °F	Yield Strength (.2% Offset) Kpsi	Tensile Strength Kpsi	Fracture Strength Kpsi	Hardness R_c	Elongation 1"	Elongation 2"	Y.S./T.S.
400	242	295	351	54	7.5	5.0	.820
550	246	288	370	53	7.5	5.0	.854
750	220	254	302	50	8.5	5.0	.866
1000	193	206	263	44	12.5	7.7	.937

Note: All results are the average of 3 specimens.
Nominal specimen thickness: .067".
Specimens were austenitized at 1700°F for 30 min. and double tempered at the above indicated temperatures for 2 + 1 hrs.

TABLE XIII

PHYSICAL PROPERTIES OF R270

HEAT TREATMENT SURVEY

PRIMARY DIRECTION

Tempering Temperature °F	Yield Strength (.2% Offset) Kpsi	Tensile Strength Kpsi	Fracture Strength Kpsi	Hardness R_c	Elongation 1"	Elongation 2"	Y.S./T.S.
400	254	325	352	55	9.0	6.5	.782
550	270	319	341	55	8.5	4.8	.846
650	265	306	338	54	7.5	4.3	.866
750	245	286	313	53	11.0	6.8	.857
850	220	265	281	50	10.0	5.8	.830

Note: All results are the average of 3 specimens.
Nominal specimen thickness: .100".
Specimens were austenitized at 1700°F for 25 min. and double tempered at the above indicated temperatures for 2 + 1 hrs.

TABLE XIV

CUMULATIVE AM355 STRESS CORROSION U-BEND TESTS

Primary (Lowest Y.S.) Direction

Test Solution	Y.S. (.2% Offset) Test Level, Kpsi	Number of Samples	Failures to Date	Average Time to Failure, days	Failure Time Range, (days)
NaCl	226 (as recvd)	6	6	3.25	0.5 to 8
$NaNO_3$	226 (as recvd)	6	none to 87 days	--	--
Na_2S	226 (as recvd)	6	none to 85 days	--	--
Na_2SO_4	226 (as recvd)	6	none to 87 days	--	--
$NaPO_3$	226 (as recvd)	6	none to 87 days	--	--

Note: Outer surface of U-bend specimens stressed beyond the Y.S.

TABLE XV

CUMULATIVE PH15-7 Mo STRESS CORROSION U-BEND TESTS

Test Solution	Direction of Specimen	Number of Samples	Failures to Date	Average Time to Failure, days	Failure Time Range (days)
NaCl	Primary	6	none to 93 days	--	--
	Secondary	6	none to 93 days	--	--
$NaNO_3$	Primary	5	none to 93 days	--	--
	Secondary	6	none to 93 days	--	--
Na_2S	Primary	6	none to 93 days	--	--
	Secondary	6	none to 93 days	--	--
Na_2SO_4	Primary	5	none to 93 days	--	--
	Secondary	6	none to 93 days	--	--
$NaPO_3$	Primary	5	none to 93 days	--	--
	Secondary	6	none to 93 days	--	--

Note: Outer surface of U-bend specimens stressed beyond the Y.S. Primary (lowest Y.S.) and Secondary (highest Y.S.).

TABLE XVI

CUMULATIVE PH15-7 Mo AND AM355 STRESS CORROSION U-BEND TESTS

Stress Corrosion Environment	Type of Steel	Sample Direction	Y.S. Kpsi	Number of Samples	Failures to Date	Average Time to Failure, days	Failure Time Range, days
Carbon Tetrachloride	PH15-7Mo	Primary	201	6	1 to 21 days	--	--
CCl_4	PH15-7Mo	Secondary	218	6	none to 21 days	--	--
(Chlorinated non	AM355	Primary	226	6	none to 21 days	--	--
hydrocarbon)	AM355	Primary	215	6	none to 21 days	--	--
Pentane	PH15-7Mo	Primary	201	6	none to 21 days	--	--
C_5H_{12}	PH15-7Mo	Secondary	218	6	none to 21 days	--	--
(Non chlorinated	AM355	Primary	226	6	none to 21 days	--	--
hydrocarbon)	AM355	Primary	215	6	none to 21 days	--	--
Trichlorethane	PH15-7Mo	Primary	201	5	none to 21 days	--	--
C_2H_2Cl	PH15-7Mo	Secondary	218	6	none to 21 days	--	--
(Chlorinated	AM355	Primary	226	6	none to 21 days	--	--
hydrocarbon)	AM355	Primary	215	6	none to 21 days	--	--

Note: Outer surface of U-bend specimens stressed beyond the Y.S.

TABLE XVII

CUMULATIVE B120 VCA STRESS CORROSION U-BEND TESTS

Secondary (Highest Y.S.) Direction

Test Solution	Y.S. (.2% Offset) Test Level, Kpsi	Number of Samples	Failures to Date	Average Time to Failure, days	Failure Time Range, (days)
NaCl, 1 M	135 (as recvd)	4	none to 176 days	--	--
$NaNO_3$, 1 M	135 (as recvd)	4	none to 176 days	--	--
$NaPO_3$, 1 M	135 (as recvd)	4	none to 176 days	--	--

Note: Outer surface of U-bend samples is stressed beyond the Y.S.

TABLE XVIII

CUMULATIVE 4137 Co STRESS CORROSION U-BEND TESTS

Primary (Lowest Y.S.) Direction

Test Solution	Austenitizing Temperature	Tempering Temperature	Number of Samples	Failures to Date	Average Time to Failure, days	Failure Time Range, (days)
NaCl, 1 M	1700°F	550	6	6	4.3	0.5 to 11.5
		750	6	4 to 344 days	--	--
		1100	6	none to 344 days	--	--
Na_2SO_4, 1 M	1700°F	550	6	6	0.9	10 min. to 2.5 days
		750	6	none to 284 days	--	--
		1100	6	to 284 days	--	--
$NaNO_3$, 1 M	1700°F	550	6	6	1.2	0.5 to 1.5
		750	6	6	33.8	29.5 to 39.5
		1100	6	5 to 284 days	--	--
$NaPO_3$, 1 M	1700°F	550	6	6	4.5 min.	3 to 6 min.
		750	6	6	0.3 days*	34 min. to 5 days
		1100	6	6	1.5 days**	0.5 to 27 days
Na_2S, 1 M	1700°F	550	6	2 to 150 days	--	--
		750	6	1 to 150 days	--	--
		1100	6	none to 150 days	--	-

* One specimen lasting 5 days not averaged.

** One specimen lasting 27 days not averaged.

Note: Outer surface of U-bend samples is stressed beyond the Y.S.

TABLE XIX

CUMULATIVE 4137 Co STRESS CORROSION U-BEND TESTS

Primary (Lowest Y.S.) Direction

Environment	Austenitizing Temperature	Tempering Temperature	Number of Samples	Failures to Date	Average Time to Failure, days	Failure Time Range, (days)
Dry Air (dessicator)	1700°F	550	3	none to 150 days	--	--
		750	3	none to 150 days	--	--
		1100	3	none to 150 days	--	--
Humid Air (satur. with water vapor)	1700°F	550	4	4	6.4	4 to 11.5
		750	4	3 to 142 days	--	--
		1100	4	none to 142 days	--	--
Laboratory (exposed directly to lab. environ.)	1700°F	550	4	none to 142 days	--	--
		750	4	none to 142 days	--	--
		1100	4	none to 142 days	--	--

Note: Outer surface of U-bend samples is stressed beyond the Y.S.

TABLE XX

CUMULATIVE ARDEFORM 301 STRESS CORROSION U-BEND TESTS

Stress Corrosion Environment	Sample Direction	Test Surface in Tension	Number of Samples	Failures to Date	Average Time to Failure, days	Failure Time Range, (days)
Sample No. 1						
NaCl, 1 M	Longitudinal	Outside (convex)	4	4	1.25	0.5 to 2
	Longitudinal	Inside (concave)	4	2 to 87 days	--	--
	Trans.	Outside	6	none to 87 days	--	--
$NaNO_3$, 1 M	Long.	Outside	4	none to 87 days	--	--
	Long.	Inside	4	none to 87 days	--	--
	Trans.	Outside	6	none to 87 days	--	--
Na_2S, 1 M	Long.	Outside	4	none to 87 days	--	--
	Long.	Inside	4	none to 87 days	--	--
	Trans.	Outside	6	none to 87 days	--	--
Na_2SO_4, 1 M	Long.	Outside	4	none to 87 days	--	--
	Long.	Inside	4	none to 87 days	--	--
	Trans.	Outside	6	none to 87 days	--	--
$NaPO_3$, 1 M	Long.	Outside	4	none to 85 days	--	--
	Long.	Inside	4	none to 85 days	--	--
	Trans.	Outside	6	none to 85 days	--	--

Note: Outer surface of U-bend samples is stressed beyond Y.S.

TABLE XXI

CUMULATIVE ARDEFORM 301 STRESS CORROSION U-BEND TESTS

Stress Corrosion Environment	Sample Direction	Test Surface in Tension	Number of Samples	Failures to Date	Average Time to Failure, days	Failure Time Range, (days)
Sample No. 2						
NaCl, 1 M	Longitudinal	Outside (convex)	6	none to 30 days	--	--
	Longitudinal	Inside (concave)	4	1 to 30 days	--	--
	Transverse	Outside	5	none to 30 days	--	--
$NaNO_3$, 1 M	Long.	Outside	5	none to 35 days	--	--
	Long.	Inside	4	none to 35 days	--	--
	Trans.	Outside	5	none to 35 days	--	--
Na_2S, 1 M	Long.	Outside	4	none to 35 days	--	--
	Long.	Inside	-	---	--	--
	Trans.	Outside	5	none to 35 days	--	--
Na_2SO_4, 1 M	Long.	Outside	4	none to 35 days	--	--
	Long.	Inside	3	none to 35 days	--	--
	Trans.	Outside	5	none to 35 days	--	--
$NaPO_3$	Long.	Outside	4	none to 35 days	--	--
	Long.	Inside	4	none to 35 days	--	--
	Trans.	Outside	5	none to 35 days	--	--

Note: Outer surface of U-bend samples is stressed beyond Y.S.

TABLE XXII

CUMULATIVE AM355 STRESS CORROSION BENT BEAM TESTS

Secondary (Highest Y.S.) Direction*

Test Solution	Approx. Tensile Stress on Sample**	Number of Samples	Failures to Date	Average Time to Failure, days	Failure Time Range, days
NaCl, 1 M	180 kpsi	6	none to 122 days	--	--
	195	6	none to 106 days	--	--
	226	6	none to 119 days	--	--
Na_2SO_4, 1 M	180	6	none to 122 days	--	--
	195	6	none to 106 days	--	--
	225	6	none to 119 days	--	--
$NaNO_3$, 1 M	180	6	none to 122 days	--	--
	195	6	none to 106 days	--	--
	225	6	none to 119 days	--	--
$NaPO_3$, 1 M	180	6	none to 121 days	--	--
	195	6	none to 106 days	--	--
	225	6	none to 119 days	--	--
Na_2S, 1 M	180	6	none to 121 days	--	--
	195	6	none to 106 days	--	--
	225	6	none to 119 days	--	--

* All samples stressed in holder to 75% of Y.S.

** The three Y.S. test levels of as-rolled material: 250 kpsi, 261 kpsi; and 302 kpsi.

TABLE XXIII

CUMULATIVE 4137 Co STRESS CORROSION BENT BEAM TESTS*

Primary (Lowest Y.S.) Direction

Austenitizing Temperature	Tempering Temperature	Approximate Tensile Stress**	Number of Samples	Failures to Date	Average Time to Failure, days	Failure Time Range, days
Marine Exposure (Kure Beach, North Carolina)						
1700°F	550°F	190 kpsi	3	3	8	3 to 16
	750	160	5	5	13	6 to 18
	1100	130	5	None to date	--	--
		tests begun 10-26-60				
Semi-Industrial Exposure (Monroeville, Pennsylvania)						
1700°F	550°F	190 kpsi	5	5	19	2 to 30
	750	160	5	5	35	18 to 45
	1100	130	5	None to date	--	--
		tests begun 10-26-60				

* Cooperative testing program with U. S. Steel Applied Research Lab., Monroeville, Pa.
** All samples surface-stressed in holder to 75% of Y.S.

TABLE XXIV

CUMULATIVE 4137 Co STRESS CORROSION BENT BEAM TESTS

Primary (Lowest Y.S.) Direction

Austenitizing Temperature	Tempering Temperature	% of Y.S. for Test	Approximate Tensile Stress	Number of Samples	Failures to Date	Average Time to Failures, days	Failure Time Range, days
Severe Industrial Exposure (Pittsburgh, Pennsylvania)							
1700°F	550°F	50	130 kpsi	6	none to 120 days	--	--
	750	50	115	6	none to 120 days	--	--
	1100	50	95	6	none to 120 days	--	--
1700	550	75	195	6	6	47.2	30 to 65
	750	75	175	6	none to 120 days	--	--
	1100	75	140	6	none to 120 days	--	--
1700	550	90	230	6	6	33.6	21 to 43
	750	90	200	6	1 to 120 days	--	--
	1100	90	170	6	none to 120 days	--	--

tests begun 3-2-61

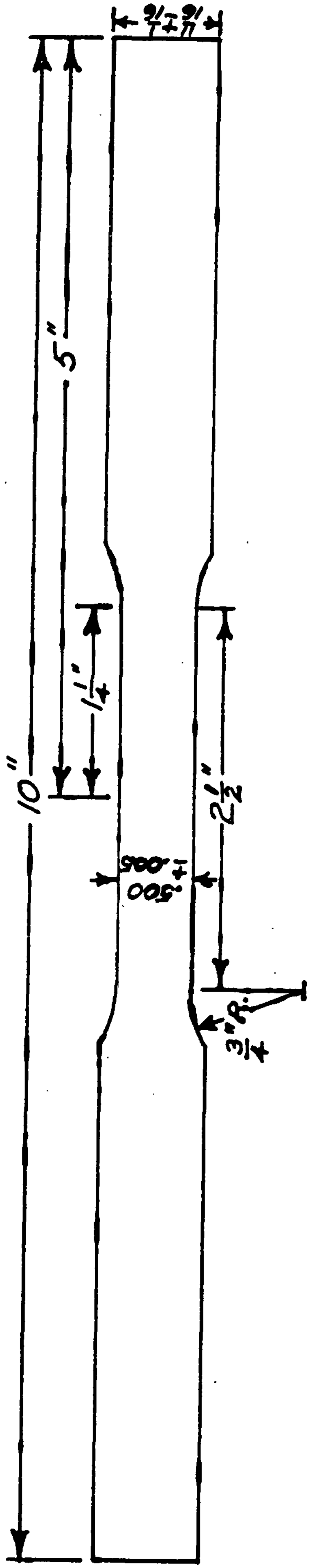

FIG. 1 FLAT TENSILE SPECIMEN

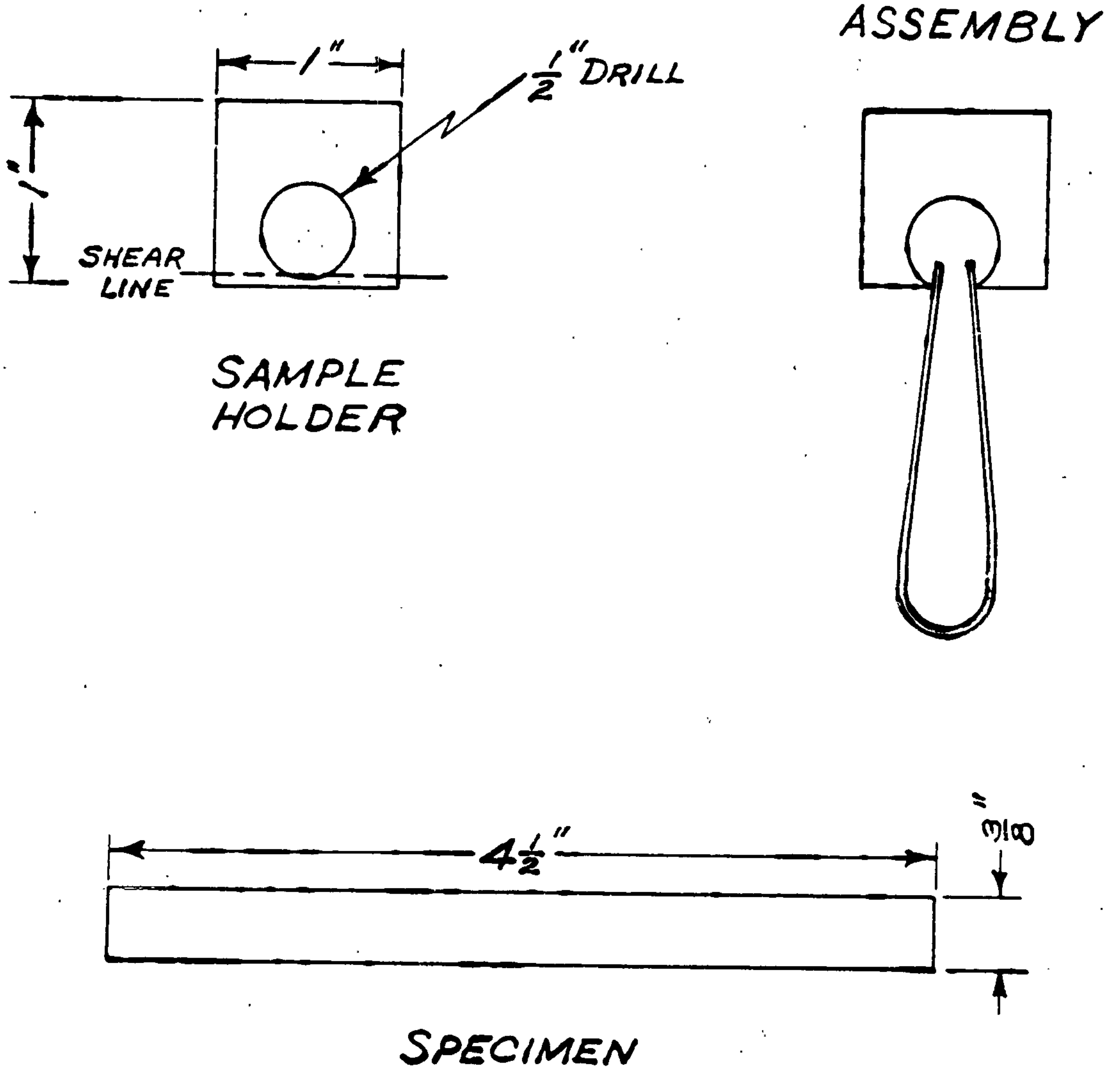

FIG. 2 THE U-BEND STRESS CORROSION SPECIMEN AND HOLDER

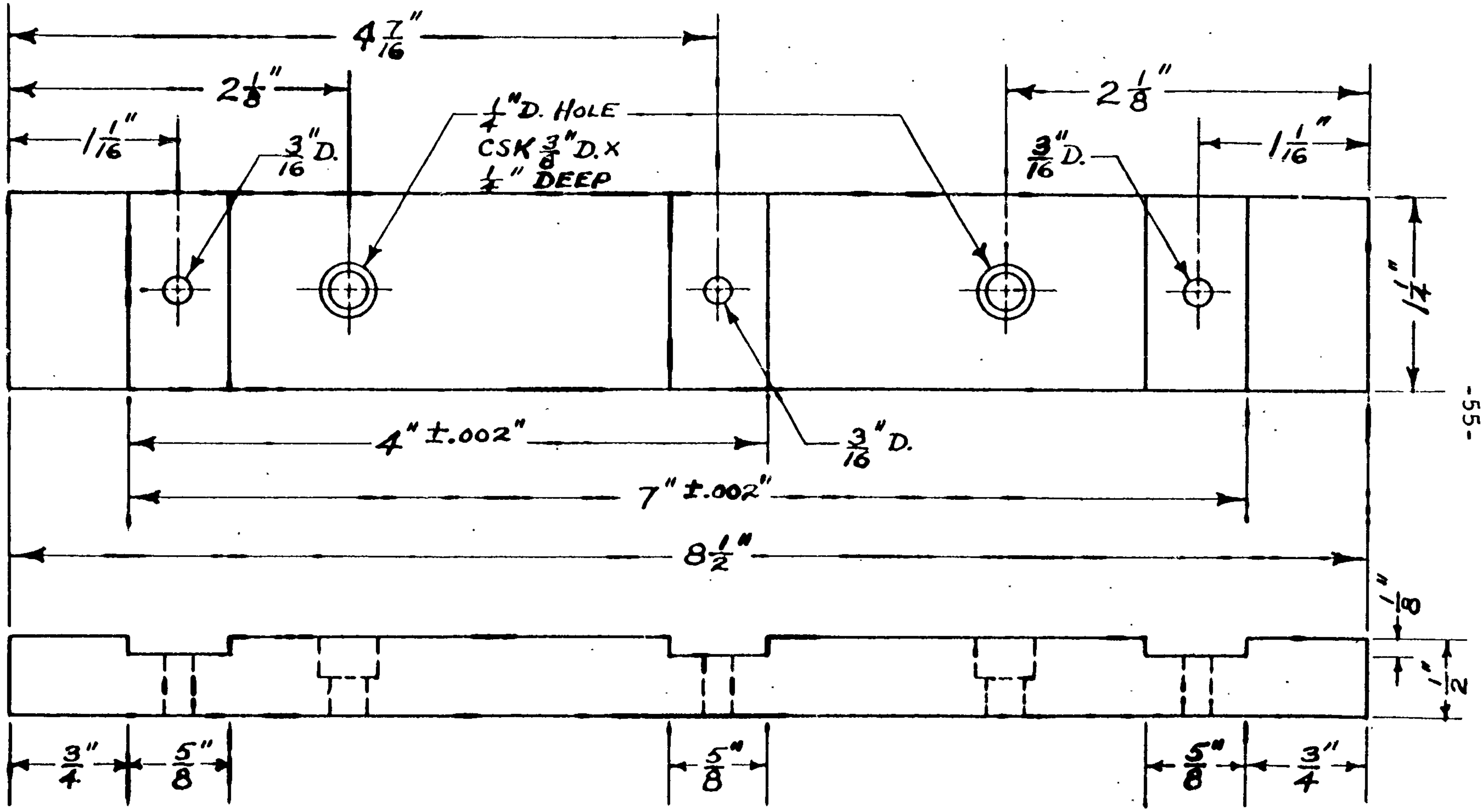

FIG. 3 SPECIMEN HOLDER FOR BENT BEAM SPECIMENS

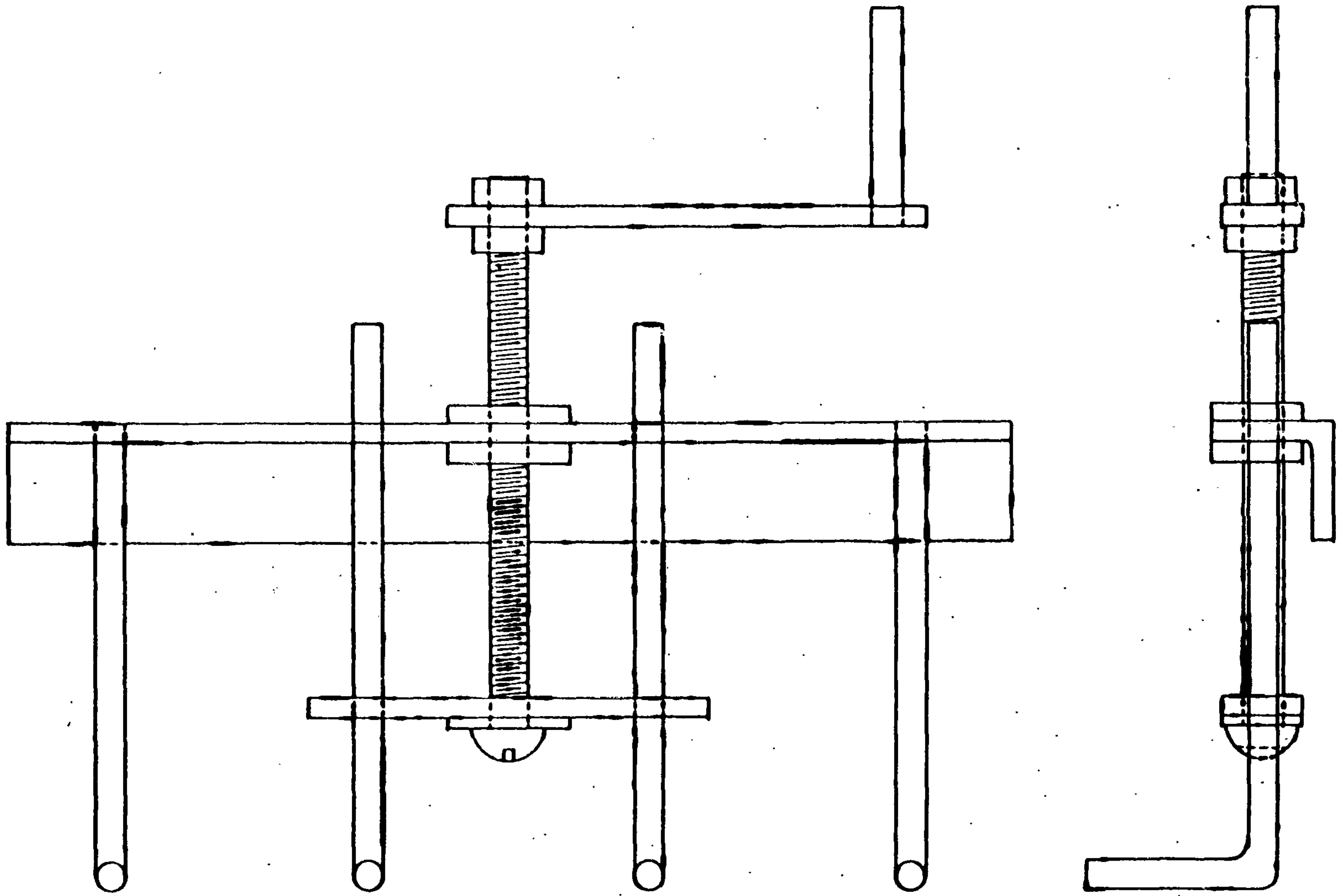

FIG. 4 SAMPLE BENDING DEVICE FOR BENT-BEAM STRESS CORROSION SPECIMENS

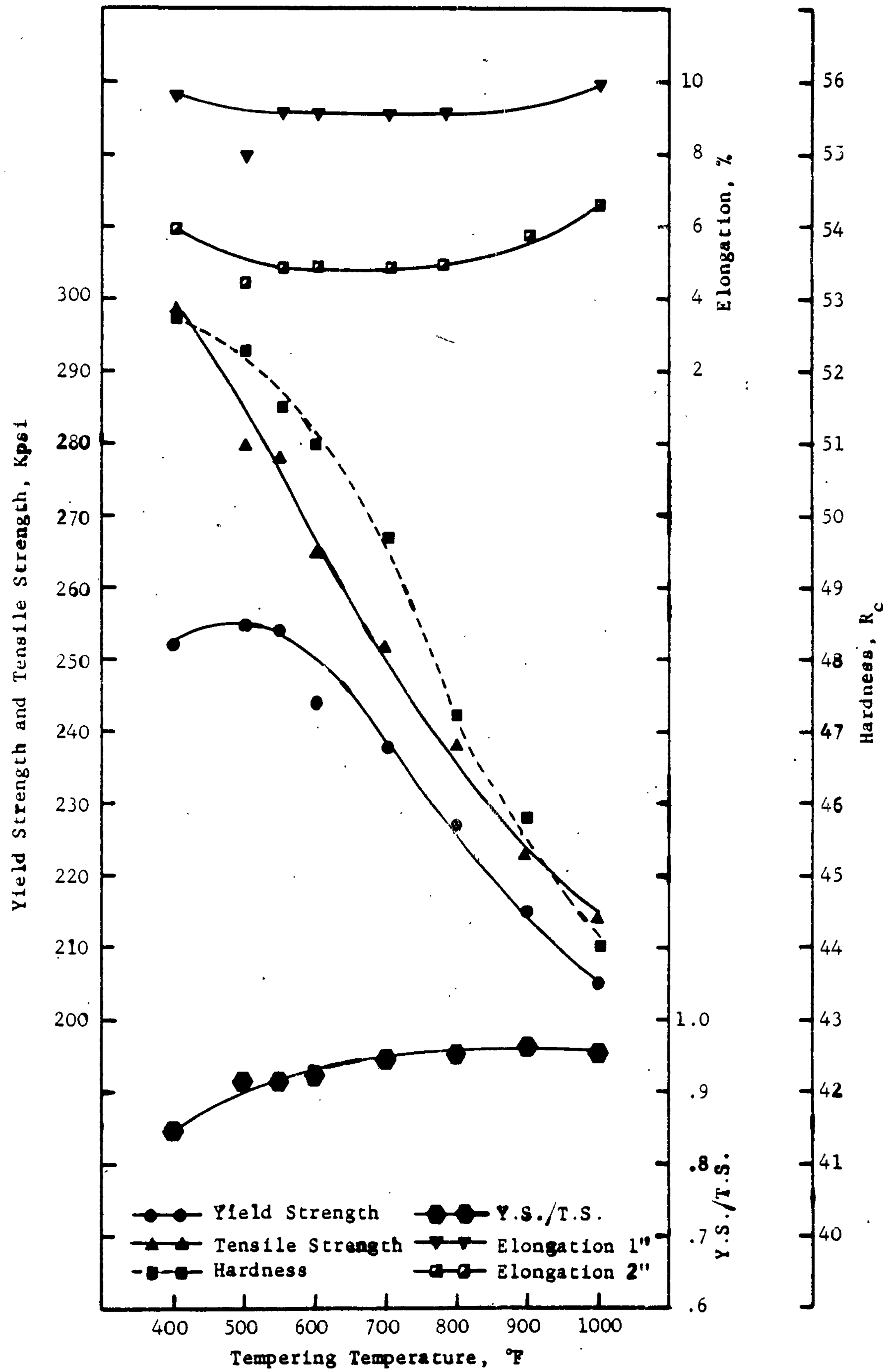

Fig. 5 Heat Treating Survey; D6Ac; Primary Direction

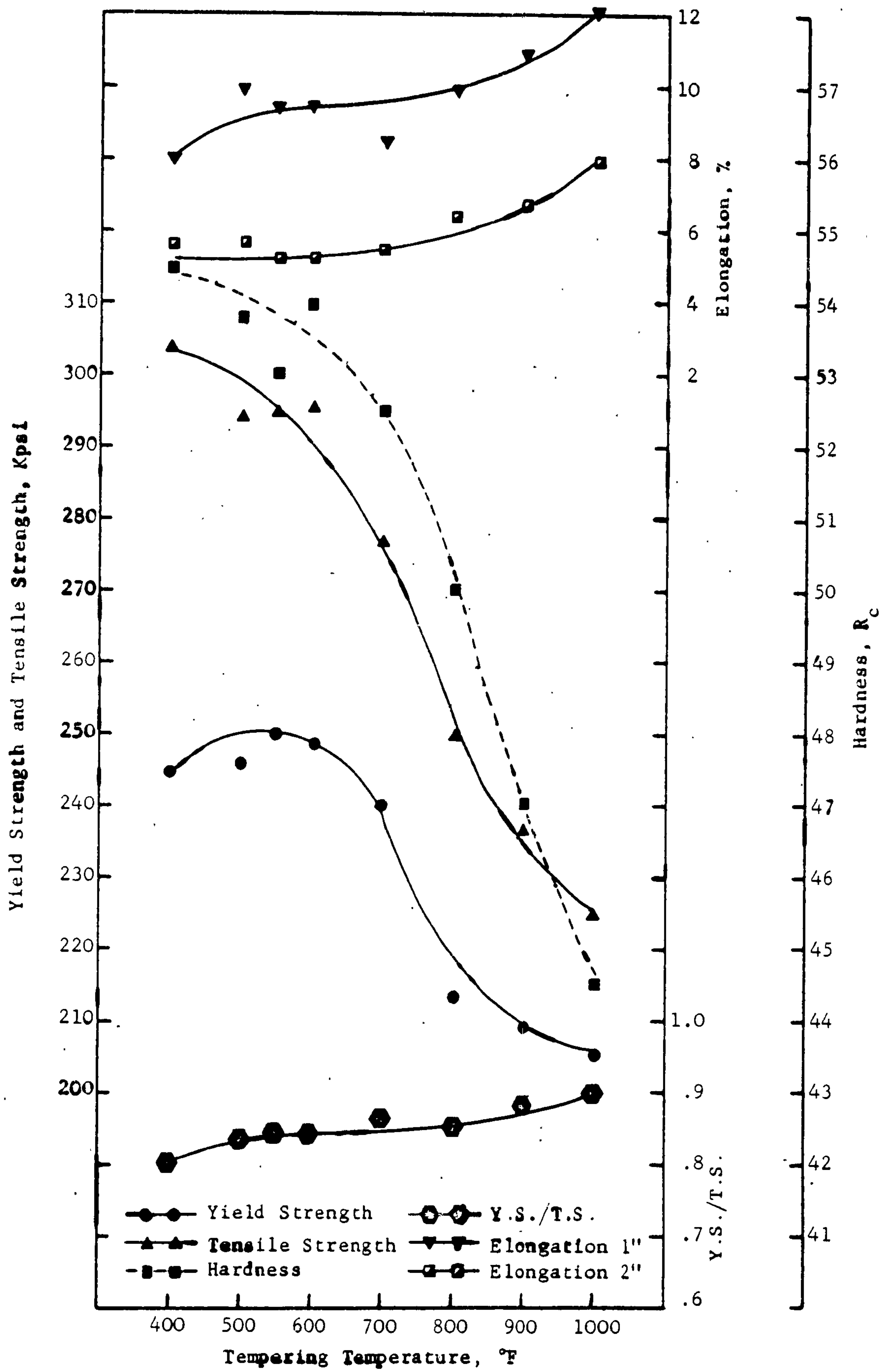

Fig. 6 Heat Treating Survey; 300M; Primary Direction

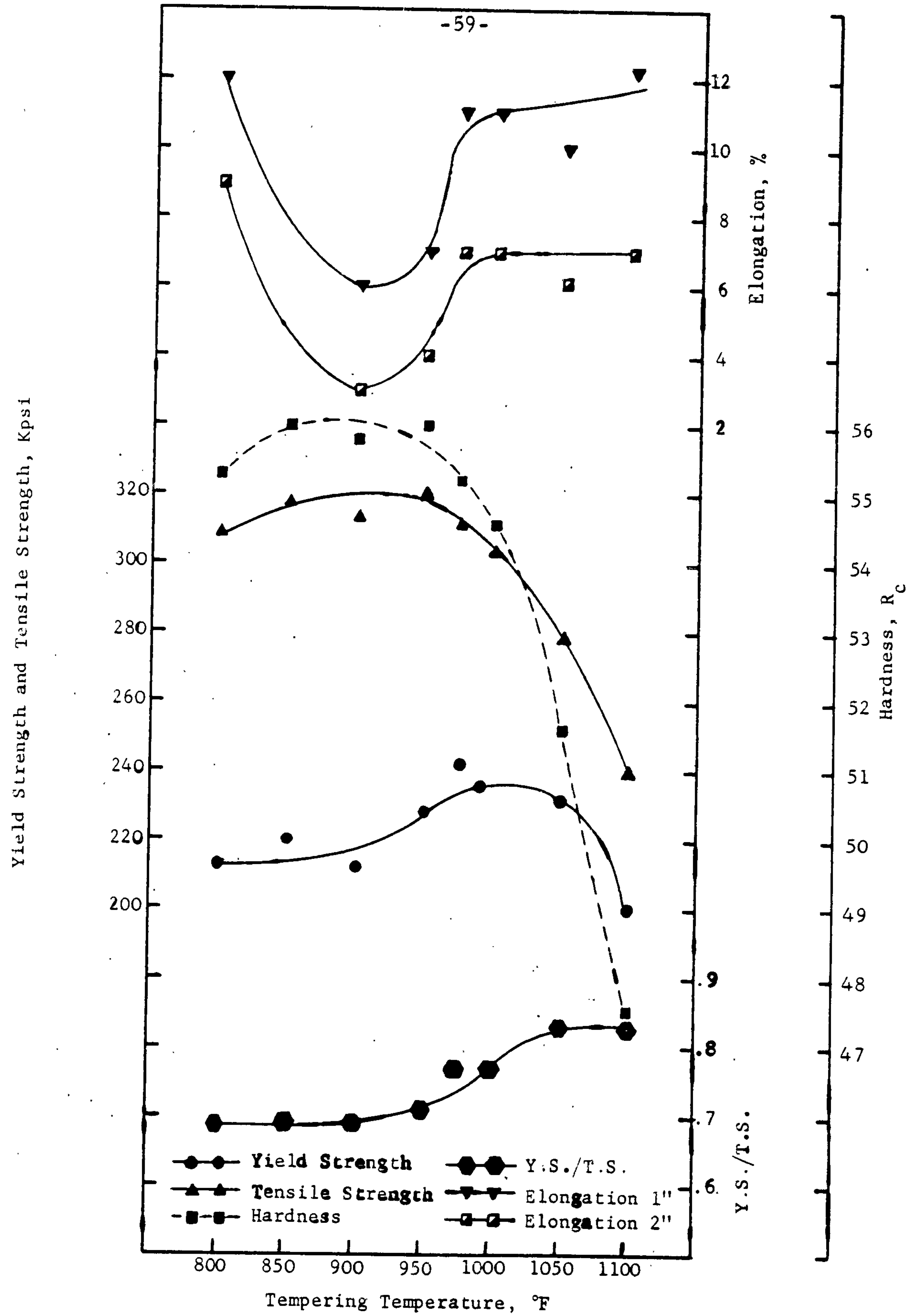

Fig. 7 Vascojet Heat Treatment Survey

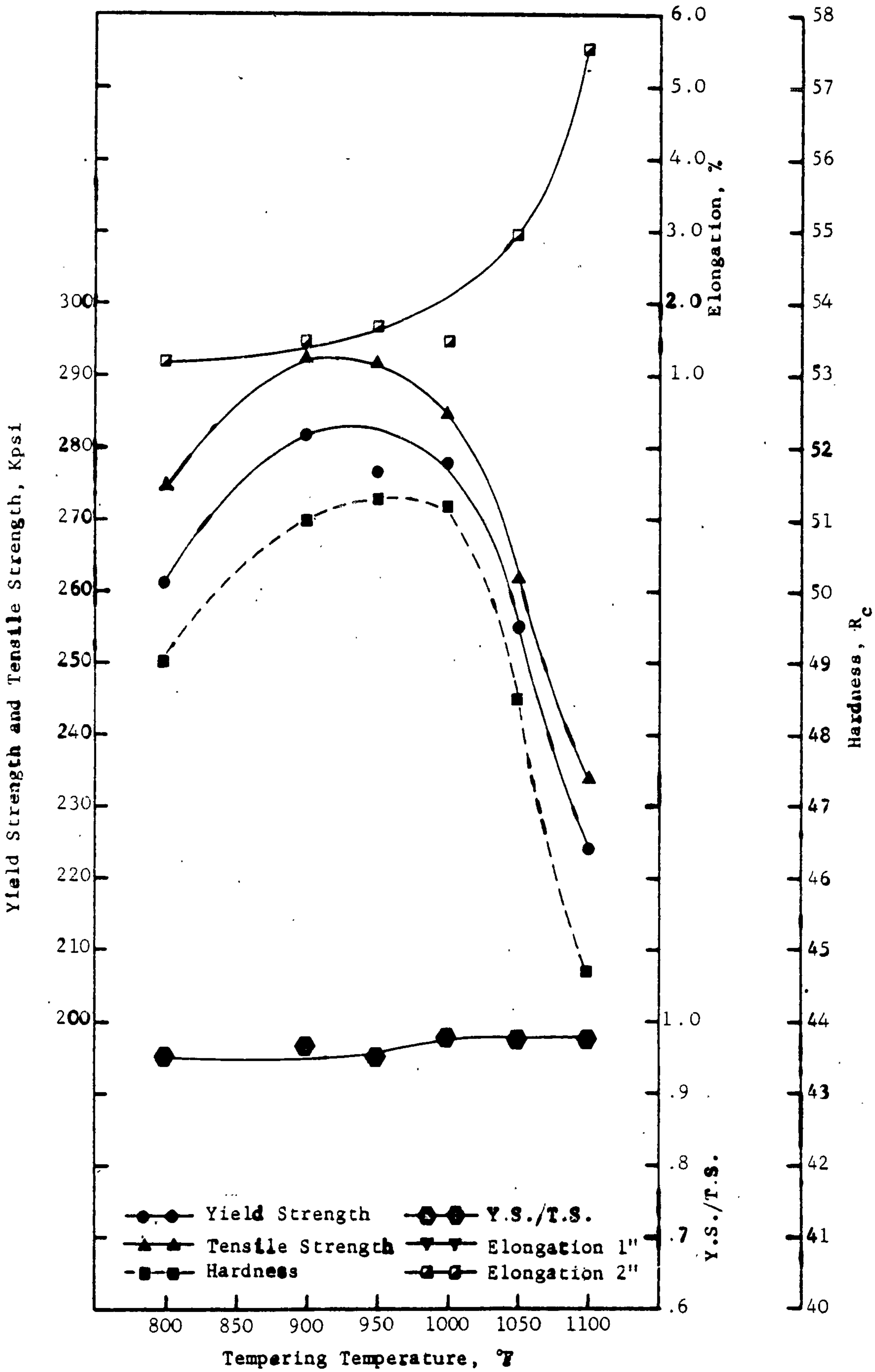

Fig. 8A Heat Treating Survey; PH15-7 Mo; Primary Direction

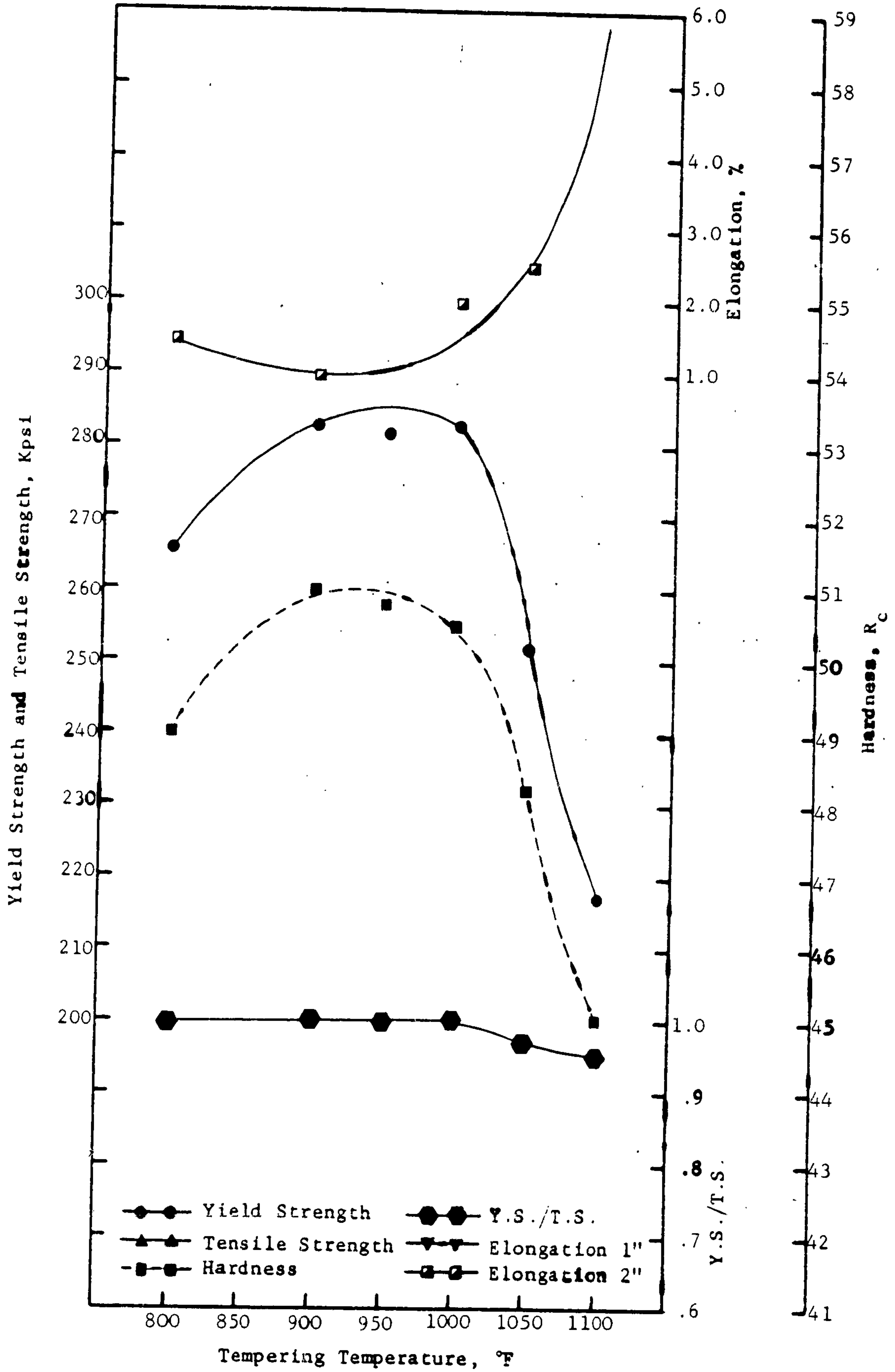

Fig. 8B Heat Treating Survey; PH15-7 Mo; Secondary Direction

Note: Tensile Curve Not Shown; Closely Duplicates Y.S. Curve

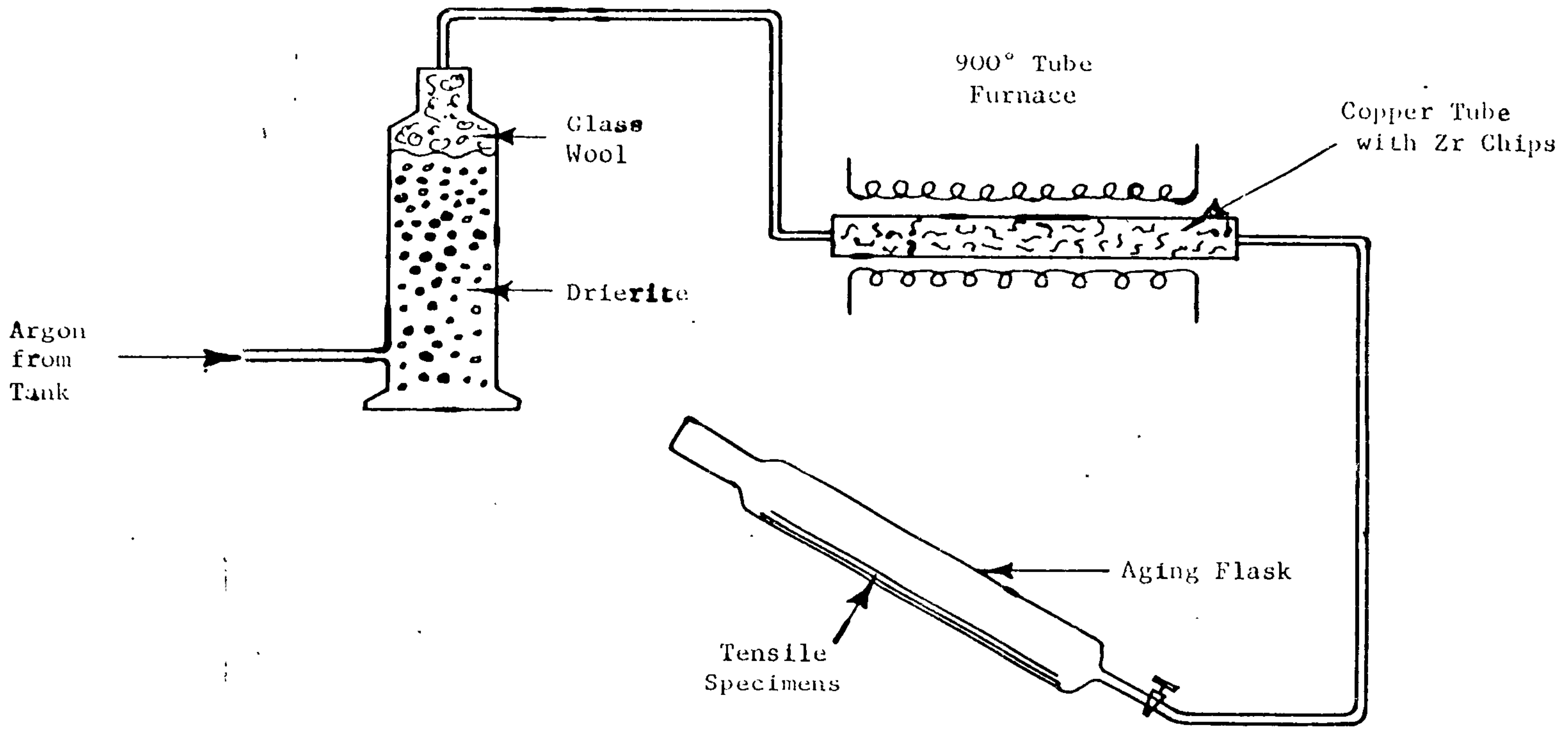

FIG. 9 SCHEMATIC DIAGRAM OF SYSTEM FOR ARGON CHARGING OF AGING FLASKS

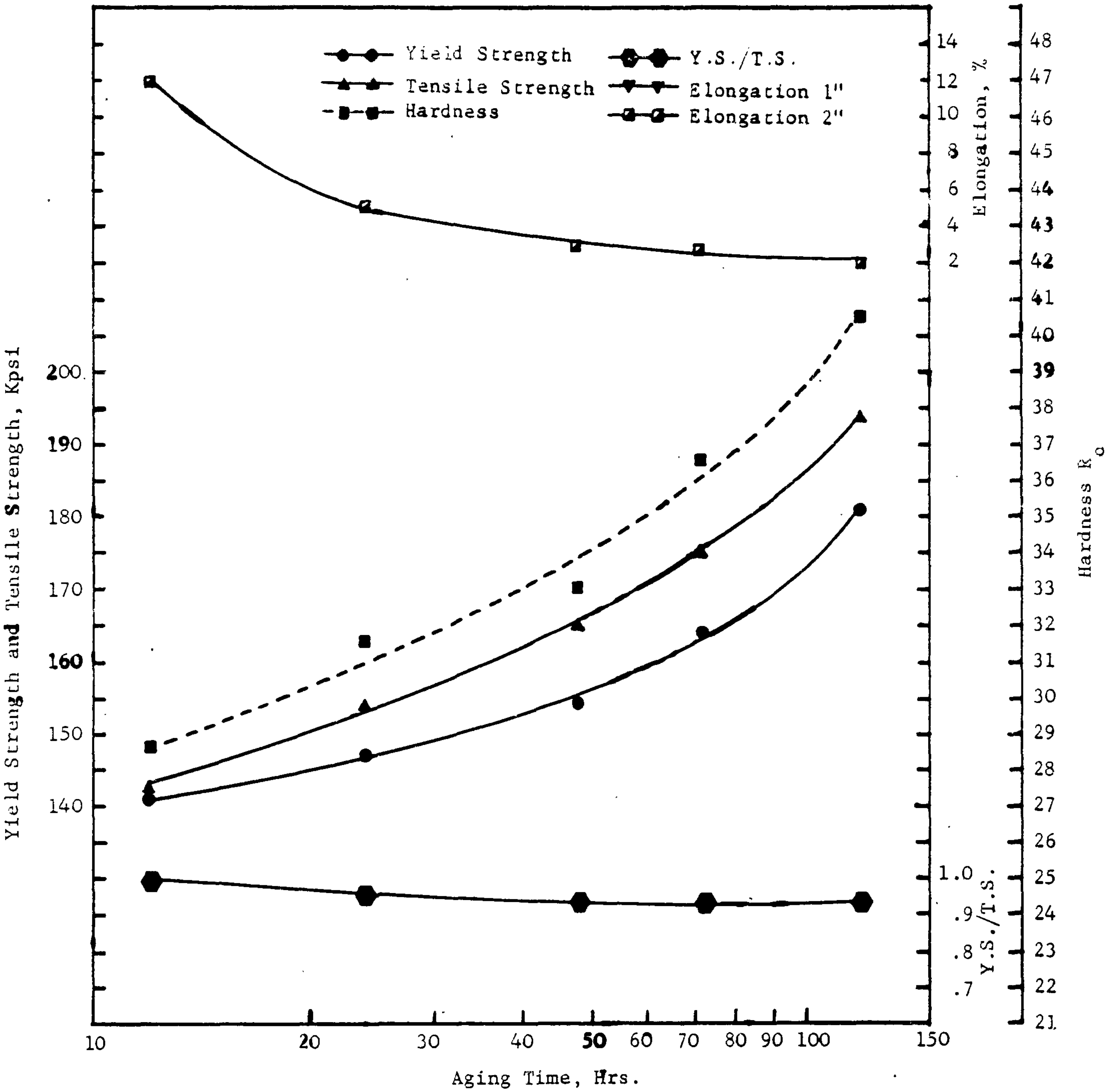

Fig. 10 Heat Treating Survey; B120VCA; Primary Direction

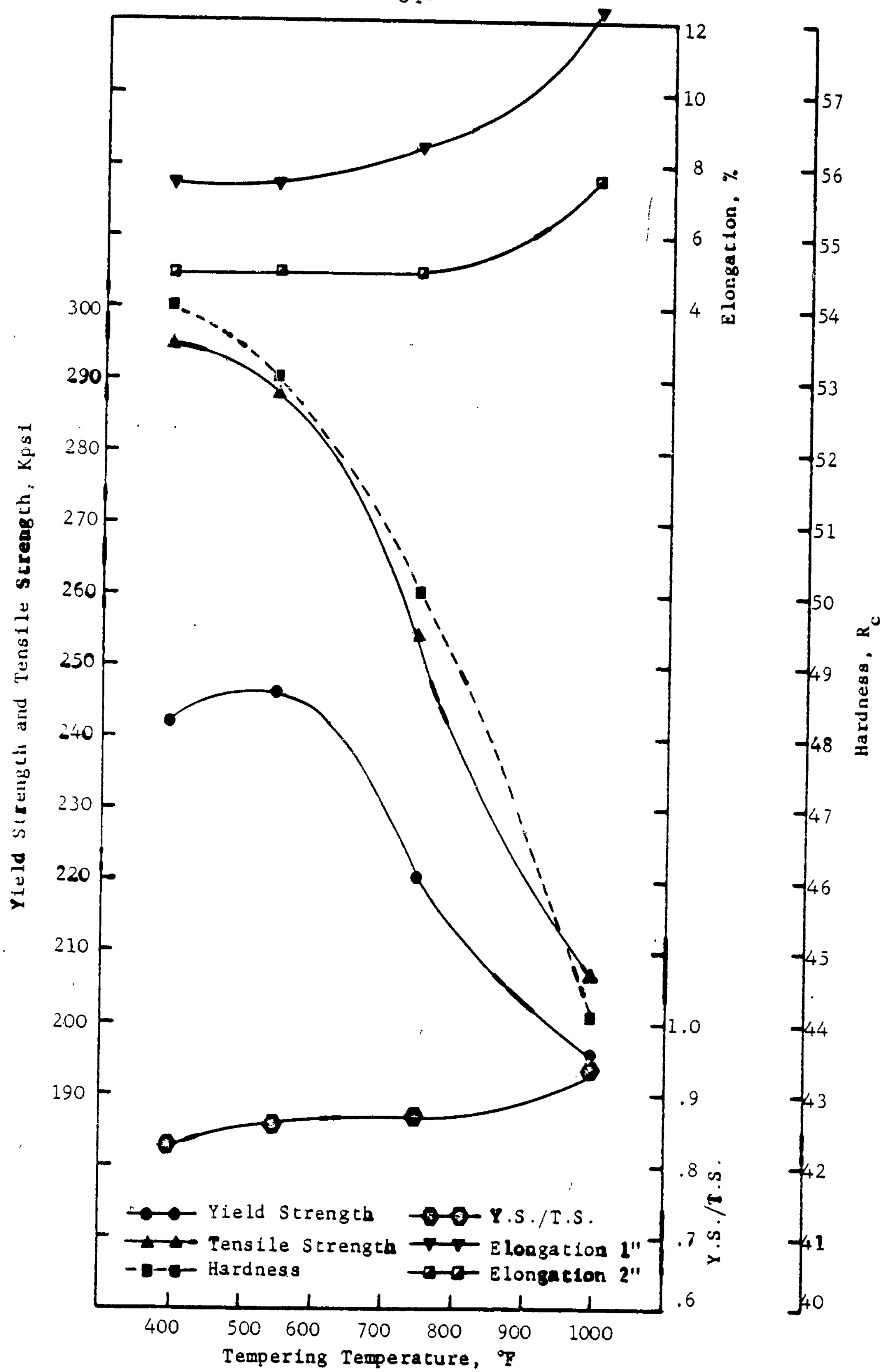

Fig. 11 Heat Treating Survey; 4137 Co; Primary Direction

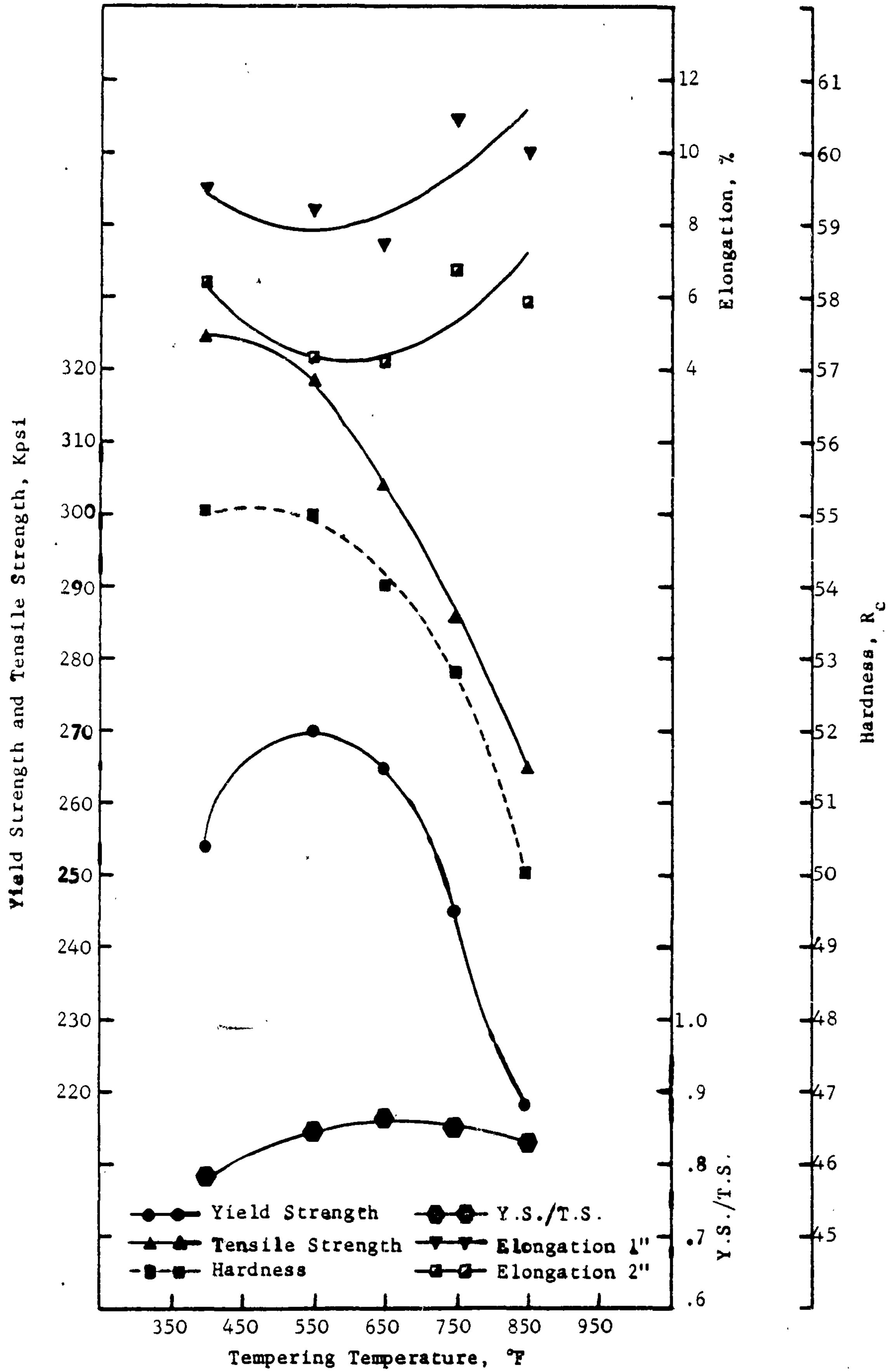

Fig. 12 Heat Treating Survey; R270; Primary Direction

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